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PENALTIES INCURRED IN USING ROCKET MOTORS OVER A WIDE TEMPERATURE RANGE

by

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SUMMARY

Liquid propellant rockets

In firing or storing rockets at low temperatures difficulties may arise due to the freezing of the fuel or oxidant, and the reduced efficiency of the ignition and injection systems. At high temperatures chemical decomposition and in some cases loss by evaporation, particularly of the oxidant, the corrosion of tanks, valves etc. by the oxidant introduce difficulties. Although some of these problems can be solved, a degradation in performance has usually to be accepted in order to meet the requirements for wide temperature limits.

Solid Propellant rockets

At low temperatures the ignition of solid propellant rockets and the maintenance of burning may be difficult. The physical properties of this type of propellant deteriorate at both temperature extremes, thus careful handling of rockets is essential at low temperatures and a definite high temperature limit is set for firing. The ballistic characteristics of solid propellant rockets vary considerably over a wide temperature range owing to the sensitivity of the rate of burning to both temperature and pressure. Although some improvement may be obtained by using interchangeable venturis, these are inconvenient and to be fully effective necessitate a degradation of performance since self-nozzling of the charge must be avoided.

The Service propellant in current use develops cracks after a very short period of storage at high temperatures and although improved types are in the development stage much work will be required before they can be regarded as cleared for Service use.

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1 Introduction

It has been suggested[1] that the selection of suitable liquid propellants for rocket motors to meet the Staff requirements for a wide temperature range should not present undue difficulty. The most serious problem appears to be the lack of information and experience, at the present time, on the effect of extreme temperatures on the injection, combustion and other processes in the rocket motor; moreover the complicated equipment required for carrying out firing tests on these motors over a wide temperature range is not available and considerable time and effort will be required in order to develop it.

As regards solid propellants, though the temperature effects are probably somewhat larger than for liquid propellants the problems involved are more clearly defined, as experience has already been acquired at extreme temperatures with small rockets. At the present time there is not available for use in the Services a British solid propellant which covers the range -50°C (-60°F) to +70°C (158°F) adequately, and though plastic propellants based on polyisobutylene seem promising, a delay of at least one to two years would be inevitable before they could be produced on the necessary scale.

2 Temperature requirements

There has been a good deal of controversy in recent years about the temperature limits required by the Services and there still appears to be some difficulty in deciding what temperature range is likely to be encountered in the Services. It has been suggested[2] that the hottest ground temperature is 77°C (171°F) in the Sahara in the sun and the coldest -55°C (-67°F) at Archangel. The low temperatures experienced by aircraft flying at very high altitudes and the high temperatures resulting from the high speed at low altitudes have not been fully investigated and it is impossible at this juncture to take them into account; they will, therefore, not be considered in this note. Suggestions for the temperature limits of armament for use in the three Services are summarized by the Ordnance Board[2] as follows:

	Storage		Functioning	
	High	Low	High	Low
Naval Service	75°C (167°F)	-51°C (-60°F)	49°C (120°F)	-34°C (-30°F)
Land Service	71°C (160°F)	-62°C (-80°F) -43°C (-45°F)	52°C (125°F)	-53°C (-65°F) -26°C (-15°F)
Air Service	75°C (167°F)	-51°C (-60°F)	66°C (150°F)	-51°C (-60°F)

Recent investigations, however, suggest that the extremes of temperature likely to be encountered are not as severe as has been suggested and that the interior of equipment is not subjected to the rigorous conditions expected from the figures given for the temperatures encountered in arctic and tropical regions.

2.1 High temperature limits

Both the temperature and the relative humidity have to be considered in assessing the effect of tropical storage conditions. In a comprehensive survey of the conditions of storage of ammunition in various theatres of war by F. G. Willson[3], it is suggested that stores exposed to the sun in desert regions may experience temperatures up to 160°F, though the

relative humidity is very low and may be of the order of 5-10%; if stores are covered the maximum temperature may be reduced by 40°F. The diurnal variation in temperature may be as much as 50°F to 60°F and the relative humidity may rise to 90% at night for covered stores. In tropical storage sheds in India temperatures up to 120°F may be experienced during the summer months and the relative humidity may vary from 80 to 90% in the monsoon season. Stores left in the sun may reach temperatures of 150° to 160°F in the North West Frontier Province of India. Average temperatures in tropical jungles are about 80°F with a relative humidity of 80%. The diurnal variation in temperature may be about 10° or 20°F, but the corresponding variation in relative humidity is very small. The seasonal variation in temperature and relative humidity is not very great.

In a report[4] on the highest temperatures encountered in the United States it is concluded from an analysis of the frequency of the occurrence of high temperatures in the Great Plains and Death Valley, California, which are considered to be the hottest parts of North America, that an air temperature of 52°C (125°F) at 5 feet from the ground is the highest which can be fairly expected in the hottest deserts and it is thought unlikely that air temperatures (at 5 feet) will remain above 49°C (120°F) for more than 4 hours; the corresponding distribution of temperature near the surface of the ground is estimated to be approximately 60°C (140°F), 74°C (165°F) and 85°C (185°F) at heights of 1 feet, 1 inch and on the ground respectively.

German experience in the last great War indicates the sort of temperatures that may be encountered in the Lybian desert. According to the records[5] taken by German Military Staff in June and July 1942 at Bir el Gynem, one of the hottest places in the Lybian desert, the temperature in the shade was never more than 50°C (122°F) or less than 20°C (68°F). Tests also showed that there was a lag of two hours before the charges stored in the shade reached their maximum and minimum temperatures; the temperatures attained by charges stored in packing cases were considerably less than the maximum and higher than the minimum recorded externally. British experience in the last war has also shown that even when cases of ammunition were left lying exposed in the desert with sun temperatures of 71°C (160°F) to 77°C (170°F) the propellant was never above 60°C (140°F)[6].

2.2 Low temperature limits

Investigations in Canada show that temperatures much below -50°C (-58°F) are very rarely encountered there and then only for short periods. Studies[7] by the United States Army of conditions at times when very low temperatures (-62°C (-80°F) or below) have been recorded show that equipment stored in extremely cold regions is likely to be cooled throughout to temperatures of -40°C (-40°F) or cooler, but even in places where the temperature drops to -62°C (-80°F) it may be only -18°C (0°F) a week earlier or later. Two maps[8] of the northern hemisphere have been made, one of the lowest temperatures that have ever been observed, and, the other of the expectancy of low temperatures. It seems advisable in studying data for guided weapons to consider only those temperatures likely to occur in regions of strategic interest for the use and storage of these weapons and also, since extreme temperatures may only occur for short periods, the temperatures likely to be encountered in equipment stored in such regions. In this way it might be possible to exclude unreal temperature limits and, therefore, avoid unnecessarily difficult research and development programmes.

The lowest temperatures that can be expected at sea are discussed in a report[9] on arctic trials carried out on board H.M.S. Vengeance, February - March, 1949. Lt. Cdr. Campbell-Cowan writes:- "During all the R.C.N. trials the lowest temperature recorded was +5°F and the coldest during the arctic trials was 10.5°F. As there has been a great deal of controversy about the extreme cold which may be encountered at sea it is desirable to determine if there is any truth in the various accounts. A check was made with the Office of the Director of Naval Meteorological Service. This Department stated that the lowest sea-going temperature recorded was 10°F. If, however, ships are to enter inlets or bays, lower temperatures than these might be expected."

2.3 Correlation of laboratory tests and climatic trials

A factor that has probably not been considered sufficiently seriously is the correlation of laboratory tests with actual climatic trials. Recent experience seems to suggest that laboratory tests may give a rather pessimistic view of the behaviour of stores and equipment in tropical and arctic conditions. For instance, according to American investigations[10] aviation fuels suffered appreciably less deterioration when stored in the desert at El Centro, California than when subjected to the corresponding laboratory tests.

2.4 Suggested temperature limits

From these considerations it appears that, to cover conditions normally encountered, a temperature range of -40°C (-40°F) to +50°C (122°F) might be adequate for the functioning of rocket motors for guided weapons and a slightly wider range of -50°C (-58°F) to 60°C (140°F) for storage. The effects of more severe conditions could be minimized by using heat reflecting paints[11] or by simple lagging.

3 Liquid propellant rocket motors

Difficulties are encountered in designing liquid propellant rocket motors for use over a wide temperature range as the performance depends on physical and chemical properties of the propellants such as the viscosity and surface tension which decrease with temperature, and the vapour pressure and corrosive action which increase with temperature; the propellants may also freeze or boil within the desired temperature range. The main fuels suitable for use in the Services, kerosene, gasoline, methyl and ethyl alcohols possess convenient freezing and boiling points (see Table I). More difficulty is encountered in selecting suitable oxidants. At the temperature limits there is not much more trouble with liquid oxygen than at moderate temperatures, but hydrogen peroxide (80% concentration) and nitric acid (98% concentration) possess freezing points that are barely adequate for low temperature use (see Table I).

In designing the components and planning the servicing and handling of rocket motors the experience gained in tropical warfare, in the use of aircraft at low temperatures[12] and in winterization trials in Canada[13] could be used. References to a considerable amount of literature on arctic problems[14] have been collected.

3.1 Storage and handling

Fuels

The storage of fuels in arctic conditions is not a very serious problem, but extra precautions would be needed in handling gasoline at these temperatures, as below 10°C there are greater risks of the formation of explosive mixtures with the air in the tanks. At low temperatures the water dissolved in kerosene and gasoline separates out and forms

minute crystals of ice; at lower temperatures wax crystals, which are somewhat larger than those of ice, are formed and may cause blockages in the feed or injection systems. At tropical temperatures also there are greater risks of the formation of explosive mixtures of kerosene with air. Desert storage tests on aviation fuels generally[10] have shown that only slight deterioration occurs after periods of storage of 12 or 18 months. Kerosene is very stable and the storage properties can be still further improved by the use of suitable oxidation inhibitors. Least deterioration is obtained when sealed drums are used for storage.

Oxidants

The main difficulties encountered in exposing stores to extreme temperatures would be with the oxidants, hydrogen peroxide and nitric acid.

Liquid oxygen

For liquid oxygen the problems would not be much more serious than those at medium temperatures; the loss by evaporation would be increased at tropical temperatures, but supplies could be replenished from a portable liquid oxygen plant, provided that the disproportionally large quantities of fuel were available for its operation. Quick and efficient methods of handling would need to be developed for both extremes of temperature.

Nitric Acid

The freezing point of nitric acid could be depressed by the addition of suitable salts though at the expense of a loss of performance and functioning. German Scientists[15] added iron salts (ferric chloride) to nitric acid to improve the ignition properties, and incidentally the freezing point was also lowered by about 10°C though serious corrosion problems were introduced. The corrosive action of 98% nitric acid especially at high temperatures is one of the most serious difficulties that has to be overcome, and suitable materials are being investigated for use with this acid. Pure aluminium seems to be a promising material and appears to have been used successfully by the Germans, though, as far as is known, not for temperatures above 40°C. Some success has been obtained with aluminium alloys for 98% nitric acid inhibited with 0.5% phosphoric acid. Aluminium pressure vessels or aluminium lined pressure vessels of suitably low weight could probably be designed which would be resistant to corrosion at temperatures up to 75°C and at the same time be capable of withstanding the feed pressures required, but more work would be required on the behaviour of nitric acid at high temperatures to determine what effect decomposition products have on the performance of rocket motors and what pressure is built up in sealed tanks during prolonged storage as first indications are that this may be as high as 30 atm in a period of one month. Since the possibility of storing rocket motors ready filled with nitric acid is being considered, corrosion prevention and methods of eliminating risks due to leakages are of fundamental importance.

Another factor that would have to be considered, if nitric acid motors had to be designed for exposure to high temperatures, is that in order to allow for the expansion of the nitric acid and the fuel, e.g. kerosene, from temperatures of about 15°C to 70°C an increase in tank space of 10%, would be required[16]. This would probably entail a relatively small increase in weight, but there would be loss of space for components and probably the disadvantage of an increase in length. A similar problem would be encountered in other propellant combinations.

Hydrogen Peroxide

The freezing point of 80% concentration hydrogen peroxide is -23°C, but recently attempts have been made in the United States[17] to produce a hydrogen peroxide with a low freezing point by adding ammonium nitrate (60% hydrogen peroxide 90% concentration/40% ammonium nitrate). This mixture has a freezing point of -37.2°C (-35°F) and should give a specific impulse of 220 lb sec/sec with J.P.1 fuel (kerosene) for a combustion chamber pressure of 500 lb/sq in. The best combustion results have been obtained with a pre-mixing nozzle in which the propellants are subsequently atomized. It is intended to use a ballistite grain for ignition in closed chambers. The loss of hydrogen peroxide by evaporation and decomposition would be much higher at tropical temperatures and cause additional servicing problems and expense; it has been stated, however, that stabilizers for hydrogen peroxide are known to be effective above 80°C (176°F)[1]. It is claimed that when stored in aluminium drums BECCO hydrogen peroxide (Buffalo Electro-Chemical Co.) only loses 1% by weight per annum at normal temperatures, though the rate would probably be considerably increased by contamination from external sources and at higher temperatures[18]. According to Professor Schumb[19] the rate of decomposition of hydrogen peroxide increases by 2.1 to 2.5 times for 10°C rise in temperature; this is stated to be valid over the temperature range 5°C to 80°C and probably also down to room temperature and up to 100°C. Investigations have shown that the ignition delay for hydrogen peroxide/hydrazine hydrate mixtures increases very little with the decrease in concentration of hydrogen peroxide resulting from prolonged storage, for instance the ignition delays at room temperature for 80% and 90% concentration are 1.5×10^{-3} and 0.9×10^{-3} seconds respectively. It can be concluded that the decomposition of hydrogen peroxide during any reasonable period of storage depending on the temperature conditions has a negligible effect on the ignition delay[17].

3.2 Functioning and performance

The operation of liquid propellant rockets is most difficult in arctic conditions as the specific impulse of the propellant combination, the propellant feed, injection and ignition systems are all adversely affected by low temperatures. For the sake of simplicity these effects, though interdependent, will be considered separately.

3.21 Specific impulse of propellant combination

The specific impulse of the commonly used propellant combinations would be reduced by 3 or 4% by decreasing the operating temperature from 15°C to about -40°C and correspondingly a slight increase in specific impulse would be obtained at +65°C. An addition of 5% ammonium nitrate to nitric acid, which depresses the freezing point by about 4°C, would cause a decrease in the specific impulse of the order of 2 or 3% for propellant combinations with this oxidant. The addition of a suitable salt to hydrogen peroxide would probably produce a similar reduction in performance.

3.22 Propellant feed systems

A change in the propellant feed pressure has an appreciable effect on the thrust for instance, for a tank pressure of 500 lb/sq in and a combustion chamber pressure of 300 lb/sq in a change in tank pressure of ±10% produces a change in thrust of ±13%. Thus although propellant feed systems operated by turbo-pumps or by compressed gases supplied, for example, by nitrogen tanks or gas generators could be used over the wide temperature range required, modifications would be needed to maintain

the correct feed pressure at all temperatures. The effect of temperature on the pressurizing system itself is considered as a separate factor as distinct from the change in feed pressure required for the efficient opperation of the injection system at temperatures considerably above or below 15°C which will be discussed in the next section.

Gas generators based on hydrogen peroxide, for example, which may be used directly or to drive a turbo-pump for propellant expulsion, would decrease in efficiency with decrease in temperature and the size of the catalyst bed would probably have to be increased by a factor of 2 or 3. The increase in the total motor weight would be relatively small, but the increase in the size and pressure drop across the catalyst bed would have to be considered. Unless carefully designed such gas generators developed to cover low temperatures would be wasteful at high temperatures.

The propellant cartridge method of feeding fuel and oxidant to the injector has the disadvantage that the rate of burning and pressure produced by solid propellant charges increase with rise in temperature. For instance, according to information supplied by I.C.I. the rate of burning of the ammonium nitrate expulsion charge used for the R.T.V.1 increases by 5% for 10°C rise in temperature and thus for a temperature range of -40°C to +60°C, there is a variation of 50%. It has been suggested by American investigators that the compartment containing the solid propellant cartridge might be heated when rockets are to be fired at low temperatures so that uniform propellant expulsion conditions could be maintained. It may be possible, however, to obtain propellant expulsion charges which are less sensitive to changes in temperature. If used for a liquid oxygen motor, a cartridge propellant expulsion system has the additional drawback that the filling time and delay before firing the motor must be reduced to a minimum in order to avoid the cooling of the charge by the liquid oxygen; thus in order to obtain known propellant expulsion conditions with the type of cartridge now used in the R.T.V.1 a specified time for filling and firing would have to be fixed for a series of ambient temperatures.

3.23 Injection systems

As the efficiency of combustion of a rocket motor depends essentially on the efficiency of the injection system, precautions must be taken to ensure that the injection system functions satisfactorily at low temperatures. H.L.M. Larcombe[20] has shown that the effect of viscosity on the flow of fluid through an injector and on the formation of the spray becomes important for high values of viscosity. As the ambient temperature decreases the viscosity of a liquid propellant increases and for temperatures below 0°C the temperature coefficient of viscosity may increase rapidly. For instances the viscosity of standard fuel as measured by investigators at the J. Lucas Laboratories[21] varies from 1.77 cp at 20°C to 11.8 cp at -40°C. Tests showed that for these high values of viscosity the flow number (rate of flow/$\sqrt{\text{pressure}}$) is reduced, and considerably higher injection pressures are required than for low values of viscosity in order to produce favourable atomization conditions. These investigations were, however, only carried out for low flow rates and these effects would not be so pronounced, for the high flow rates of the propellants in rocket motors.

Rough estimates according to the method proposed by H.L.M. Larcombe[20] suggest that at temperatures of about -40°C the injection pressure would probably have to be increased by about 5% for the fuels gasolene, methyl alcohol and ethyl alcohol and the oxidant nitric acid. Similar effects would probably be obtained for hydrogen peroxide. For kerosene the corresponding increase in injection pressure required would probably be

about 40%. At high temperature the effect of the change in viscosity on the injection system would be slightly less and the injection pressure would be 2 or 3% too high. It is difficult to assess the influence of these effects and the increase of the surface tension of the propellants at low temperatures on the atomization and combustion, but recent experiments[22] on the ignition delay at low temperatures for white fuming nitric acid and furfuryl alcohol with additives to lower the viscosity suggest that the increase in viscosity of the propellants had probably less effect on injection than might be expected. It appears from experiments on different types of spray nozzles[23] that an increase in surface tension has very little effect on the discharge coefficient of the swirl plate nozzle and none on the size of the air core. Though it caused a slight decrease in the cone angle of the spray and in the tangential velocity, it did not produce any significant change in the axial velocity. Due to differences in the conditions of flow the increase in the frictional resistance produced different effects on the flow in different types of nozzles. In the swirl plate nozzle, as the viscosity increased from 2 to 50 centistokes the axial velocity and radial velocity increased, whereas in the helical groove nozzle the axial velocity increased and the tangential velocity decreased. It is possible, however, that the overall loss in efficiency of the injection system when the rocket is fired at -40°C might lead to a decrease in thrust of 10%; correspondingly a slight increase in thrust would be obtained at 65°C. Only slight variations in oxidant/fuel ratio would be likely to occur if the injection systems were modified to suit the ambient temperature and, as the curves for the specific impulse against mixture ratio have a relatively flat maximum, these variations would probably have little effect. Research would be needed, however, in order to obtain experimental data on the effects of low temperature on atomization, combustion, etc.

3.24 Ignition systems

The difficulties of starting a rocket motor increases with decrease in temperature. There is an increase in the ignition delay, and also more danger of the accumulation of combustible mixtures in the combustion chamber and hence greater risks of explosion; devices could, however, be developed to reduce the hazards due to the long ignition delays or failures.

Very little information is available on ignition at very low temperatures, though it appears to depend mainly on the rate of chemical reaction. For hydrogen peroxide and hydrazine hydrate fuel with catalyser the ignition delay varies from about 16×10^{-3} sec to 1×10^{-3} sec over the temperature range 0°C to 100°C[18]. Ignition delay tests[22] on nitric acid (96% concentration) and hydrazine-water eutectic composition (freezing point -59°C) and mixture ratio (oxidant/fuel) approximately 1/1 gave ignition delay values of 33 and 60 milliseconds at temperatures of 75°C and -40°C respectively. Reliable ignition was obtained at 75°C, but at -40°C the ignition delay was becoming excessive and below this temperature ignition was unreliable. Low temperature ignition appeared to be better for fuel rich mixtures.

The main methods of ignition of rocket motors could probably be modified so that they would function effectively at low temperatures. Pyrotechnic igniters are in common use especially for the one shot operation usually required for guided missiles and this type of igniter could probably be used over a wide temperature range.

The use of a primer fuel, which is fed into the combustion chamber just ahead of the main fuel, is probably not particularly suitable for

guided missiles, but if required this method could be used over a wide range of temperatures provided that at low temperatures care was taken to employ primer fuels with suitable low temperature ignition characteristics. W.A.F.1 (70% furfuryl alcohol/30% aniline) has been used successfully for the ignition of nitric acid/kerosene motors at normal temperatures, but no data are available on its effectiveness at low temperatures; it is unlikely that it would be effective for temperatures as low as -40°C. Methyl alcohol or ethyl alcohol/nitric acid systems might present less difficulty at low temperatures than nitric acid/kerosene systems. Hydrazine type primer fuels could be used for both nitric acid and hydrogen peroxide motors and metal alkyls, if carefully excluded from contact with the air for liquid oxygen motors. Screens, or target plates coated with suitable catalysts, could be used at low temperatures, though larger quantities of catalysts would probably be needed as the speed of reaction decreases with temperature.

The spark or glow plug type of igniter, which has proved successful for the ignition of liquid oxygen/paraffin motors, could be used over a wide temperature range, but for low temperatures, a higher electric input would be required.

Pilot combustion chambers and staged rocket motors would offer certain advantages at low temperatures, but would add weight and complexity to motor units.

3.25 Motor components and materials

For the combustion chamber of rocket motors required to operate in arctic, temperate and tropical conditions suitable materials are needed which retain the desired chemical and physical properties over a wide temperature range. Aluminium and aluminium alloys are obviously useful materials, as previously mentioned, since they can be used with hydrogen peroxide (85% concentration) and nitric acid (98% concentration); they may also possess adequate strength for an efficiently cooled combustion chamber. Unlike most metals, they have greater resistance to shock loads at low temperatures so that they can be used in arctic conditions. Stainless steels can also be used, but have the disadvantage that the supply is not adequate for large scale use; there is, however, the possibility that certain nickel steels with adequate impact strength at low temperatures could be used.

Suitable steels and aluminium alloys are available for valves and other components to cover the temperature range required, but the choice of material for valve seatings, seals, gaskets etc. is restricted and difficulties of supply and expense are involved if the rocket motors are required to operate at both temperature extremes; for instance rubber becomes brittle at -60°C. Materials such as silicones (for hydrogen peroxide only), Kel F (polymonochlortrifluorethylene) or Teflon (polytetrafluorethylene) which has good physical properties and is resistant to nitric acid and hydrogen peroxide over a temperature range of -70 to 250°C, would be required for use with these oxidants.

The operation of valves and other components over the required temperature range would have to be considered in designing rockets for severe arctic and tropical conditions, but it is unlikely that any major modifications or appreciable increase in weight would be involved. The sudden change in temperature from extreme tropical temperatures to the low temperatures reached at high altitudes, as well as the change in pressure and humidity might affect the behaviour of delicately adjusted mechanisms, but this is more likely to affect the guidance and control equipment than the rocket motor components.

3.26 Monopropellant systems

Monopropellants based on ammonium nitrate, which are now being investigated at R.P.D., are attractive for use in the Services on account of the ease of handling, but, at this early stage, they could not be used at temperatures much below 0°C unless provision were made for supplementary heating. This added complexity may be worth-while in view of the (predicted) much greater safely and relatively simple construction of the motor compared with that of similar bipropellant motors.

3.3 Discussion

The penalties incurred when liquid rocket motors are used at temperatures down to -40°C can be summarized by reference to a nitric acid/methyl alcohol motor as follows:-

(a) Loss in specific impulse of the propellant combination 3 - 4% (comparison with specific impulse at 25°C)

(b) Loss in specific impulse due to addition of 5% ammonium nitrate to lower freezing point of nitric acid about 3%

(c) Loss in specific impulse due to less efficient injection, atomization and combustion (for suitably modified motor) probably very small

(d) Decrease in thrust if propellant feed pressure reduced by 10% about 15%

(e) Less efficient cooling due to increase in viscosity of coolant for nitric acid as the coolant; the liquid film heat transfer coefficient might be reduced by 80% under very unfavourable conditions.

At high temperatures, on the other hand, the specific impulse and thrust would be slightly increased (which would give a considerable variation in performance over the whole temperature range), but the problems of corrosion would be very severe and an increase in size would be required to allow for the increased space required in the propellant tanks to allow for the thermal expansion of the propellants.

4 Solid propellant rocket motors

Solid propellants are being considered for both the main propulsion unit and the boosts of guided weapons, but the main disadvantage of using them over a wide temperature range is that the mechanical and ballistic properties are sensitive to changes in temperature. Mechanical considerations demand the rather difficult requirement that the propellant should not be brittle at the low temperature limit and yet not be too soft at the high temperature limit to withstand its own weight or acceleration forces. At the same time ballistic considerations demand the requirement, equally difficult to fulfil, that the pressure produced by a charge burning at the low temperature limit should be high enough to produce stable combustion and yet that produced at the high temperature limit should not be so high that unduly thick-walled tubes have to be used to prevent bursts.

There are no British solid propellants available which can adequately cover the range from -50 to +60°C and those in general use have the following undesirable characteristics from the point of view of a wide temperature range:-

1 Brittleness at low temperatures

2 Low values of Young's modulus at high temperatures

3 Large variation in performance with change in temperature

4 Inability to withstand high temperature storage

It is possible, however, that the defects may be considerably reduced by improving existing colloidal and plastic propellants of developing new types.

4.1 Colloidal propellants

Double base propellants have the advantage of relatively high specific impulse, but the physical properties of the nitrocellulose nitroglycerine colloid, (the main constituents) are very sensitive to changes in temperature. The precise effect of temperature on the functioning and performance of colloidal propellants depends on the charge composition and design.

4.11 Functioning at extreme temperatures

Low temperatures

At -20°C double base propellants become brittle and at temperatures below this their ability to withstand the sudden impacts incurred on ignition is greatly reduced. The low temperature limit of the "Terrier" missile,[17] which uses cast double base propellant, is about -7°C, but it has been suggested that if a smaller igniter were used to reduce the violent pressure rise on ignition, this limit might be reduced below -20°C.

At low temperatures burning may tend to become unstable if the particular motor is designed to operate at a low pressure at 25°C, since the rate of burning decreases with both decrease in temperature and pressure. The low temperature burning properties of cordites have been improved slightly by the addition of potassium cryolite as in SU/K; for some motors burning has been achieved at a temperature of -23°C for pressures as low as 230 lb/sq in by using igniter-maintainers.[20]

Recent tests indicate that small SU/K motors can function satisfactorily at much lower temperatures than the specified low temperature limits. P.D.E. trials[25] carried out in 1943 showed that cruciform 11 SU/K charges functioned correctly down to -40°C. The rounds were stored at a temperature of -39 to 42°F (-39.4 to -41.1°C) for 12 hours previous to firing; 19 rounds were fired statically and all functioned satisfactorily. No audible firing delay occurred and no unburnt cordite remained in the tube after firing. The mean time of burning for 16 rounds was 2.15 seconds compared with the corresponding value of 2.17 seconds for 4 rounds fired at -20°F (-28.9°C) the lowest temperature at which they had previously been fired.

In trials[26] carried out in Canada in the winter of 1948-49 British 3-inch rockets consisting of steel tubes containing cruciform charges of SU/K/X/11 functioned satisfactorily when fired from static mounts at temperatures down to -49°C; this type of rocket was also fired successfully at arctic temperatures from aircraft. The low temperature limit for these rockets was originally given as -21°C. No ignition failures and no irregularity of burning were observed, although the burning time was increased and varied slightly. Similar results were obtained with

American H.V.A.R. (high velocity anti-aircraft rockets) consisting of steel tubes containing cruciform grains of ballistite. It was impossible, however, to measure the thrust, pressure and time of burning owing to lack of equipment and further trials are needed in order to assess the effect of temperature on performance.

High temperatures

The upper temperature limit for tubular and similar charges of cordite is largely governed by the Young's modulus of the propellant. The tubular charge is not supported by the motor body and thus it is liable to failure by barrelling; this type of charge, therefore, is not suitable for use at high temperatures except when it is manufactured in a hard composition. This defect is reduced in the cruciform charge, which is partially supported by the tube walls and successful results have been obtained with 3-inch charges of SU/K when fired at 63°C. Star centre charges are however, considered to be preferable as no grid is required, the loading density of the charge is high and the hot gases are to a large extent prevented from reaching the walls of the tube.

Since motor tube walls are made as thin as possible to keep the weight to a minimum cordite rockets are liable to fail when fired at high tropical temperatures on account of the high pressures produced, especially if the burning surface is accidentally increased as for instance by the formation of cracks.

4.12 Performance at extreme temperatures

It is difficult to give general figures for the effect of temperature on the performance of colloidal propellant rocket motors as this depends on both the charge composition and design.

According to recent figures[24] for a given rocket motor the variation in the mean working thrust over the temperature range -23 to +66°C is probably not greater than ±25% with a corresponding variation in total impulse of ±6 to 8%. The mean working thrust and total impulse may, however, vary at one temperature by 10% from one lot of propellant to another of the same nominal composition, though the variation is usually about 3 to 5%; within any one lot the variation from round to round is about 1 to 2%, but may be as much as 5%.

In comparing the 'overall specific impulse' of a rocket at the high temperature limit with that at a medium temperature, for instance about 15°C, both the increase in specific impulse and increase in motor tube thickness and weight must be considered. The increase in specific impulse is only of a small order probably about 5%. The increase in pressure when the charge is burned at the upper temperature limit may, however, be of the order of 70%, thus the thickness of the motor tube wall and hence the weight of the tube may be increased by 70% (if the minimum thickness of tube is used at 15°C). For steel motor tubes the weight of the tube may be about 1/3 of the weight of the filled motor and, therefore, the percentage increase in the total weight of the motor may be less than 20% if allowance is made for the safety factor tolerances, the minimum thickness for screw threads and other considerations; this may give a loss of about 15% in the 'overall' specific impulse at the upper temperature limit. It has been suggested by American investigators[27] that for one of their solid propellant motors the case weight could immediately be reduced by 15% if charges were always fired at 25°C.

The variation in the burning time, thrust and specific impulse of colloidal propellant rocket motors with temperature introduces difficulties in meeting specified requirements and also complicates the problem

of guidance and control. Although these difficulties could be reduced by the use of interchangeable venturis there would be some loss of performance since 'self-nozzling' must not occur with the largest venturi and the loading density is, therefore, only at the optimum when the largest nozzle is used; in other words a higher density of loading would have been possible, if the rocket were to be fired only at moderate temperatures. This method is, therefore, more suitable for low performance rocket motors such as assisted take off units for aircraft than for boosts for guided missiles.

Double base propellants with improved temperature characteristics have been achieved by adding lead stearate to slow burning compositions so that plateau form pressure/burning rate curves have been obtained. It is claimed that the pressure index of the American extruded double base propellant H8 has been reduced from 0.7 to 0.15 over the pressure range 1200 to 2000 lb/sq in and the temperature coefficient of pressure from 0.8 to 0.5% per °C.[5] If similar results or the 'Mesa' effect[28] (so called on account of the elevated plateau in the burning rate/pressure curve) could be obtained with somewhat faster burning compositions solid propellant boost rockets might be developed for guided missiles to give more uniform performance over a wide range of temperatures.

4.13 Effect of storage and rough handling

One of the most serious difficulties with double base propellants is that during storage at high temperatures gases are emitted due to decomposition; the rate of gas production appears to increase more rapidly at temperatures above 60°C. The cracks produced by this process in SU/K increase the burning surface and hence when a rocket is fired after hot storage abnormally high pressures may be developed and cause bursts.

Investigations are being carried out on the development of improved non-cracking colloidal propellants both in this country and in the United States. R. J. Rosser[29] has shown that high rates of gas evolution are produced when carbamite is used as a stabilizer and cordites with a longer cracking life have been obtained by reducing the carbamite content.

It is suggested by American workers[30] that cast double base propellants have a longer cracking life than extruded types of a similar composition. It has also been shown that the use of 2 nitro diphenylamine instead of ethyl centralite in any propellant leads to the production of less gas.

According to H. Grosse[5] the production of gas increases with the nitrogen content of the nitro-cellulose and he considers it desirable to keep the nitrogen content to medium values between 12.25 and 12.65%, although higher values improve the burning characteristics at low temperatures. H. Grosse also suggests that gassing at high temperatures increases with the humidity content and that improved compositions might be obtained by replacing nitroglycerine and nitro cellulose by non-hygroscopic components such as nitroguanidine.

With coated charges the nitroglycerine diffuses into the inhibitor layer, and at the same time the organic esters used as plasticizers in the coating material counter diffuse into the adjacent cordite; these two processes modify the burning rate, and thus cause a gradual tailing off in the thrust instead of the usual fairly sharp cut off. Tests have shown that after a coated cordite charge with cellulose acetate used as the inhibitor was stored for 21 days at 60°C the burning rate and specific impulse were decreased by 7% and 8% respectively.[24] By using ethyl

cellulose, which compared with cellulose acetate has less than half the affinity for nitroglycerine and contains only 10% plasticizer, these diffusion effects are reduced considerably. Cordites undergo chemical deterioration during storage and after exposure to a temperature of 60°C for 3 months there is a decrease in the tensile strength.[31] As stated in a recent report[3] it has been shown fairly conclusively that the chemical deterioration of explosives increases exponentially with increase in temperature, the temperature coefficient remaining approximately constant up to about 140°F (60°C) and then increasing progressively beyond this temperature. Since cordite has a temperature coefficient of deterioration of about 1.8 per 10°F (0.32 per 10°C) a storage period of 5 years at 90°F (32°C) is equivalent to about 3 months at 140°F (60°C). The effect of humidity has to be added to the pure temperature effect and the worst storage conditions are a high humidity combined with high temperature. According to O.B. Proc. U 2,782 the 'chemical' life of cordite SU/K when stored at 32°C is taken to be 25 years, but a period of 5 years is suggested for cordite rocket motors since the falling off in the value of the Young's modulus of the propellant is the determining factor; in a later O.B. Proc. 35,033 (U 2848) a life of 9 years is suggested for assembled cordite subject to annual proof at the upper temperature limit and provided that the storage conditions are not more severe than indicated in U 2,782.

From the results of trial it has been estimated that a period of storage of 3 months at 49°C or a shorter period at 60°C would probably not affect appreciably the functioning of 3-inch rockets filled with SU/K cruciform charges. There might, however, be some increase in peak pressure, though probably very little change in working pressure and rate of burning. There is limited experience of the effect of inhibitive coatings on the storage life, and of SU/K charges of thick web, but there are indications[32] that inhibitive coatings do not affect the time of storage before cracks appear, although they apparently increase the extent to which the cracks develop. The diffusion effects observed with coated charges during high temperature storage have already been mentioned.

No particular difficulties are encountered with the chemical instability of conventional colloidal propellants during low temperature storage. Very few arctic trials have been carried out with colloidal propellant rocket motors at very low temperatures, but the British 3-inch rockets filled with SU/K cruciform charges apparently showed no ill effects due to two years storage at temperatures down to -49°C.[26] Colloidal propellants, however, become brittle at about -20°C and their ability to withstand rough usage is much reduced. In order to overcome this difficulty compositions with improved low temperature characteristics are being investigated and long chain explosive plasticizers for replacing nitroglycerine are being studied in the United States.[30] For the same purpose a collection of data on the viscosities of dilute nitrocellulose solutions in various plasticizers is also being assembled in an attempt to find a solution with a small temperature coefficient of viscosity.[30]

4.2 Plastic propellants

4.21 Functioning at extreme temperatures

Plastic propellants are intended to adhere to the walls of the motor tube and have the advantage over colloidal propellants that for a wide range of temperatures they remain soft enough to relieve the strains resulting from the differential expansion or contraction of the charge and rocket motor tube as the temperature changes. One of the

disadvantages of the current type of plastic propellant based on a polystryene pol-α-methylstyrene binder is, however, that they are not suitable for arctic use since they have a brittle point at about -20°C.

R.D.2043 (containing sodium nitrate and ammonium picrate), which was intended for use in the R.T.V.1 boost with a burning time of 3.8 seconds, has been fired successfully over a temperature range of -21°C to +60°C. This propellant is to be replaced by R.D.2201 which contains ammonium perchlorate in the place of sodium nitrate and has a higher specific impulse than R.D.2043 though similar temperature limits.

Tests[33] with two types of R.D.2049 (61% and 20% softness respectively) have shown that the softness of the propellant has a considerable effect on the functioning at extreme temperatures; 4 out of 6 charges of the harder propellant burst when fired at -40°C, whereas only 1 out 11 charges of the softer propellant were unsuccessful.

4.22 Performance at extreme temperatures

The specific impulse of the above types of propellant with sodium nitrate as oxidant is about 150 to 170 lb sec/lb and that of propellants with ammonium perchlorate as oxidant may attain a value of 220 lb sec/lb. The changes in the mean working pressure and total impulse over the range -23 to 66°C are of the order of ±13% and ±5% respectively, but the lot to lot variation is usually greater than for Service colloidal propellants.

"Platonized" or 'Mesa' type propellants are of great value in obtaining more uniform ballistic characteristics over a wide temperature range as well as in saving weight, but up to the present platonized propellants have only been obtained in slow burning compositions and 'Mesa' type propellants are not available in this country.

4.23 Effects of storage and rough handling

As plastic propellants based on polystyrene poly-α-methylstyrene become brittle at about -20°C they are unable to withstand rough usage below this temperature. Charges tend to crack owing to the differential expansion and contraction of the propellant and motor tubes with change in temperature.(The linear coefficient of expansion of plastic propellant is 10 and 5 times greater than that of steel and light alloys respectively). Hycar lacquer is used to improve the adhesion of the propellant to the rocket tube and rounds with this type of lacquered tube behave reasonably satisfactorily after being subjected to cycling trials over the temperature range 0 to 60°C.[24]

During high temperature storage or temperature cycling plastic propellants based on a polystyrene poly-α-methylstyrene binder tend to become hard and cracks may be formed which cause an increase in the burning surface and greater risks of bursts when the rocket is fired. Tests have shown that, when charges of R.D.2043 were stored at 60°C for two weeks followed by 12 weeks at 49°C the burning rate was increased by 15% when the rockets were fired at -21°C and by 5% when they were fired at 60°C.[24] It is suggested that when charges are fired at high temperatures cracks which may have developed probably seal themselves as the propellant is soft and the differential expansion is such that the crevices tend to close up. At low temperatures, on the other hand cracks are more serious, since the propellant is harder and more brittle and at the same time the differential contraction tends to enlarge the crevices, thus cracks that have been developed are not self sealing. For rockets which have been stored at high temperatures allowance must, therefore, be made for the effect on the performance of the rocket of high

temperature storage in addition to the effect of the ambient temperature at the time of firing.

The hardness of a given composition of plastic propellant is determined to a certain extent by the particle size of the solid constituents; thus for propellants with a certain proportion of solid constituents by weight a propellant containing fine particles will be harder throughout the whole temperature range considered than one containing coarse particles. On the other hand, it has been suggested that the hardness produced during the high temperature storage of a plastic propellant may be a function of the viscosity of the binder since this determines the rate of setting up of the particle/particle contacts by the solid constituents. From this point of view the high temperature storage behaviour might be improved by increasing the viscosity of the binder. In an attempt to obtain a binder with the desirable properties of a high viscosity and low temperature coefficient of viscosity together with a low brittle point investigations are being carried out by E.R.D.E. on polyisobutylene.[34] With polystyrene poly-α-methylstyrene binders the brittle point is raised as the viscosity is increased so that no advantage in temperature range is gained; on the other hand with binders based on polyisobutylene the brittle point is at first reduced as the viscosity is increased and then remains constant as the viscosity is further increased. Polyisobutylene binders have been obtained with a brittle point at about -50°C and a viscosity of the order of 10^6 poises. Tests show that rounds with propellants based on polyisobutylene composition R.14 and otherwise similar in composition to R.D.2201 withstand temperature cycling between -60 and +75°C rather better than the propellants based on polystyrene poly-α- methylstyrene withstood the narrower range of -10°C to +75°C.

Propellants based on a polyisobutylene binder appear to be promising since they possess improved mechanical and wide temperature storage characteristics, but ignition is difficult and the performance and variation in performance with temperature are similar to those of propellants based on the older binder. Although there is a fair prospect of this new type of propellant proving successful, especially for small motors, it is in an early stage of development and extensive research and trials are required.

4.3 American composite propellants

Fairly extensive investigations have been carried out in the United States on composite propellants, which are claimed to have very good temperature characteristics, but further practical experience is required with these propellants before their value can be fully assessed. If these propellants were considered for use by the United Kingdom the difficulties involved in adapting American propellants for British rockets should not be overlooked. Two types of American composite propellants are briefly discussed in order to indicate some of the advantages they might offer in reducing the penalties involved in meeting temperature requirements. The data are based mainly on reports of visits to American Establishments by British Scientists.

4.31 Composite propellants with Thiokol rubber binder

Composite propellants with a Thiokol rubber binder have high cohesive and impact strengths and remain elastic over a wide temperature range; charges have been made up to 15 in. in diameter. It is claimed[17] that charges can be stored at -71°C without developing cracks and after storage at this temperature for 3 months are reported to show the same pressure time curves as fresh charges. The temperature limits are said

to be about -50°C to +70°C for loose inhibited charges, but bonded charges have a narrower range than this. The specific impulse at 1000 lb/sq in is between 175 and 200 lb sec/lb. Ammonium perchlorate compositions have been produced for which it is claimed that the pressure exponent has been considerably reduced, whereas for compositions with only potassium perchlorate as oxidizer the pressure exponent is 0.8.[6] Thiokol propellants are stated to be easy to ignite, but they have the disadvantage that they are erosive to metals and require a graphite throat; they also produce large quantities of smoke and disagreeable fumes;

4.32 Composite propellants with paraplex resin binder

Solid propellants based on ammonium or potassium perchlorate and a paraplex resin binder should give a specific impulse up to 200 lb sec/lb and about the same variation in performance with temperature as Thiokol propellants; the rate of burning is said to increase by about 0.5% per °C rise in temperature above 60°C and about 0.4% per °C below 60°C. The temperature limits are claimed to be -50°C and +70°C. It is possible that charges of almost any size could be made; steel tubes are used and refractory inserts are needed for the throat.

4.4 Discussion

The penalties involved in using the three main types of solid propellants for rocket motors in guided weapons over a wide range of temperatures are summarized in Table III. The extruded double base propellants used in the Services have the advantages that they possess a high specific impulse and are readily available, but they have the disadvantages that their performance and physical properties vary considerably with temperature; the storage and handling properties are also adversely affected by extreme temperatures. Although improved compositions have been obtained in which some of these disadvantages are reduced, it is probable, in view of the inherent properties of double base propellants, that the limit of what can be achieved has almost been reached and any further small improvement will be at the cost of considerable effort. There is, however, a prospect of obtaining solid propellants, which meet the temperature requirements, by developing plastic propellants based on polyisobutylene binders, since these have improved mechanical properties over a wide temperature range and give a performance slightly less dependant on temperature than conventional colloidal propellants. The overall specific impulse attainable is probably of about the same order as for double base propellants. A reduction in weight might be achieved and the use of interchangeable venturis avoided if platonized or 'Mesa' compositions were developed for fast burning motors.

If propellants based on polyisobutylene do not materialize, it may be necessary to consider the use of American composite propellants or, on the other hand, to develop two types of propellant one for the arctic-temperate and the other for the tropical-temperate range.

5 Conclusions

5.1 Liquid propellant rocket motors

On the basis of the low temperature properties nitric acid and methyl or ethyl alcohol would probably be the most suitable propellant combination for use in rocket motors over wide temperature ranges in the Services, though difficulties would be encountered at high temperatures owing to increased corrosion by the oxidant and greater hazards with the fuel. The most serious problem, however, for any propellant combination would be to start rocket motors safely and efficiently at low temperatures. The loss in 'overall' specific impulse of a low freezing point

nitric acid/methyl alcohol motor at -40°C would probably be less than 10%, if suitable modifications were made in the feed, injection and ignition system and in the various components; there would also be a restriction in the choice of materials.

It seems probable that liquid propellant motors with a relatively small change in performance over a wide temperature range could be developed for guided weapons without the need for designing different types of motor and using different propellants for arctic and tropical conditions, but it should be realized that the use of rocket motors even at medium temperature is only at an early stage and that practically no experience has been gained in liquid propellant rocket techniques at extreme temperatures as no facilities exist for this work; a great deal of research covering a wide field would, therefore, be required to enable rocket motors to be used efficiently and with the minimum risks at arctic and tropical temperatures. This type of motor is a comparatively complicated mechanism for use in the Services and at low temperatures, where even the simplest task requires a major effort, considerable difficulty would be encountered in developing techniques for handling dangerous liquids and preparing for rocket firings to ensure that acidents were reduced to a minimum, especially as personnel must be dressed in cumbersome arctic clothing. The low temperature limit at which these motors could be used would probably be determined by factors of human endurance; to give an instance, at temperatures as low as -32°C there is a danger of the lungs freezing due to over exertion followed by deep breathing.[35]

5.2 Solid propellant rocket motors

For immediate use in the Services extruded double base propellants, such as SU/K cordite are the only British solid rocket propellants which have been tested extensively enough and are in sufficient supply to be considered for even the restricted range -40°C to +60°C; the usefulness of these propellants to the Services, is however, limited by their short storage life in tropical conditions and inability to withstand rough usage at arctic temperatures, unless suitable protective measures are taken.

For use in the future, modifications of double-base propellants with wider temperature limits may become available; but there seems to be a fair prospect of attaining a temperature range (for storage and functioning) of -50 to +70°C for small motors with plastic propellant based on polyisobutylene for which the change in performance is probably slightly less than for Service double base propellants.

Very good temperature characteristics are claimed for American composite propellants, but difficulties of obtaining supplies of raw materials would be entailed in adapting these propellants for use in British rockets.

The main penalty, however, that should not be underestimated is that to use rockets for guided weapons over a wide range of temperatures considerable effort and time would be required for carrying out the extensive research and trials that are necessary and this effort might be disproportionately large compared with that entailed by the Services in using comparatively simple methods for protecting rockets from extreme temperatures.

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TABLE I

Boiling points and freezing points of common propellants

Propellant	Freezing point °C	Boiling point °C
Gasoline	-60	Over range 40 to 200
Kerosene (SR 312)	-40	Over range 153 to 288
Methyl alcohol	-98	65
Ethyl alcohol (95%)	-117	78
Furfuryl alcohol	-32	171
Hydrazine	+2	114
Hydrazine Hydrate	-40	119
Aniline	-6	184
Liquid hydrogen	-259	-253
Liquid oxygen	-218	-183
Hydrogen peroxide (80%)	-23	131
(90%)	-10	142
Nitric acid (98%) (95%)	-51	89
(99%)	-42	86

TABLE II

Penalties involved in use of common oxidants for rocket motors over wide temperature limits

		LIQUID OXYGEN	HYDROGEN PEROXIDE	NITRIC ACID
Storage and handling	Low Temperatures	No storage difficulties anticipated Servicing and handling techniques in arctic conditions need to be developed	No storage difficulties anticipated Effect of freezing on stabilized H.T.P. not known, probably not serious. Servicing and handling techniques in arctic conditions need to be developed	No storage difficulties anticipated Servicing and handling techniques in arctic conditions need to be developed
	High Temperatures	Greater loss by evaporation Additional servicing and handling problems and expense for replacement of oxidant Greater ullage space required to allow for expansion of fuel and probable increase in length of motor	Greater loss by evaporation and decomposition Shorter storage life Additional servicing and handling problems and expense for replacement of oxidant Greater ullage space required to allow for expansion of propellant and probable increase in length of motor	Serious corrosion problems. Possible effect of corrosion products on specific impulse and general performances needs to be considered Servicing and handling more difficult Greater ullage space required to allow for expansion of propellant and probable increase in length of motor
Functioning and performance	Low Temperatures	Loss in specific impulse of propellant combination due to decrease in temperature (probably of the order of 3% for common fuels at -40°C comparison with performance at 15°C) Modifications required to improve less efficient propellant feed, injection, ignition and cooling systems, atomization and combustion Methyl or ethyl alcohol probably most suitable of common fuels Greater risks when firing than at normal temperatures	Low freezing point H.T.P. required Loss of specific impulse of propellant combination due to decrease in temperature and addition of salt to lower freezing point (probably less than 10% comparison with performance at 15°C) Modifications required to improve less efficient propellant feed, injection, ignition and cooling systems, atomization and combustion Methyl or ethyl alcohol probably most suitable of common fuels Greater risks when firing than at normal temperatures	Low freezing point nitric acid required Loss in specific impulse of propellant combination due to decrease in temperature and addition of salt to lower freezing point (probably less than 10% comparison with performance at 15°C) Modifications required to improve less efficient propellant feed, injection, ignition and cooling systems, atomization and combustion Methyl or ethyl alcohol probably most suitable of common fuels Greater risks when firing than at normal temperatures
	High Temperatures	Small increase in specific impulse of propellant combination Modifications required in propellant feed and other systems to cover high as well as low temperatures Greater risks in firing than at moderate temperatures	Small increase in specific impulse of propellant combination Small loss in specific impulse and increase in ignition delay after high temperature storage Modifications required in propellant feed and other systems to cover high as well as low temperatures Greater risks in firing than at moderate temperatures	Small increase in specific impulse of propellant combination Possible loss in specific impulse due to corrosion products Modifications required in propellant feed and other systems to cover high as well as low temperatures Greater risks in firing than at moderate temperatures

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TABLE III

Characteristics of main types of solid propellants for rocket motors

		Colloidal propellants (Extruded and cast double base)	Plastic propellants Polystyrene poly-α-methyl styrene (Type 1) Polyisobutylene (Type 2)		American composite propellants (Thiokol rubber base)	(Paraplex resin base)
Functioning and performance	Variation in performance with temperatures	Large	Smaller than for colloidal propellants		Claimed to be small	
	Temp. coeff. of press $\left[\left(\frac{1}{p}\frac{dp}{dT}\right)_K\right]$ (°C)	0.4 to 1.4	0.4		0.2 to 0.3	0.5 to 0.6
	Pressure index n ($r = bp^n$)	0.5 to 0.8	0.25 to 0.7		0 to 0.8	0.4 to 0.8
	Temp. limits (functioning)	Approx. -40°C to +80°C	Approx 0 to 60°C (e) (Approx. -50°C to +80°C for P.I.B.)		Claimed -50 to +70°C	Claimed -50 to +70°C
	Loss in performance at extreme temperatures	Probably up to 10% though loss at high temperatures (a)	Probably about 5%			
	Reproducibility of ballistics	Fairly good	Poor; depends on particle size of oxidant		Not fully known, further trials required	
	Other penalties		Smoke and fumes; erosive to metals Extensive research and service trials required for propellants with P.I.B. binder		Smoke and fumes Erosive to metals; refractory inserts often required. Extensive trials required	
Storage and handling	Low temperatures	Brittleness and inability to withstand rough handling Some difficulty with inhibitors at very low temperatures	Type (1) Brittleness and inability to withstand rough handling	Type (2) Good mechanical properties and ability to withstand rough usage compared with (Type (1)	Good mechanical properties and ability to withstand rough handling, though bonding to wall tends to fail for large charges	Good mechanical properties though cracks are liable to develop at the points of star centre or similar charges
	High temperatures	Very short storage life (b), 3 months at 140°C High percent wastage Longer cracking life for C.D.B. (c)	Short storage life owing to cracking. Cracking and separation of charge from motor tube on temperature cycling propellants hygroscopic	Improved storage life compared with type (1)	Long storage life	
	Effect of storage on performance	Cracks in propellant charges likely to produce marked change in shapes of pressure/time curves. At the upper temperature limit bursts may occur particularly if safety factor small; light alloy tubes would certainly give trouble with cracked charges. Progressive fall in Young's modulus leads to gradual reduction in upper temperature limit	Cracks have serious effects at low temperatures but tend to be self sealing at high temperatures	Effects less serious than for Type (1)	Claimed to be small	
Availability	Material	For extruded double base propellants no particular difficulty; raw materials imported, but readily available	Sodium nitrate readily available for bulk supply, but bulk supply of ammonium perchlorate restricted (Electrical power is also required)		Not available in this country	
	Plant	Extruded double base - large scale manufacturing capacity. Cast double base (d) - laboratory scale manufacture (higher precision claimed) Curing equipment not available	Small scale manufacture Type (2) propellants in early stage of development			
	Remarks	High specific impulse attainable. Some success with 'Platonization' and 'Mesa' effects and non-cracking compositions	Sodium nitrate propellants have low S.I. and are very smoky. Ammonium perchlorate propellants have high S.I., but are liable to give rise to secondary peaks. There is a vague suggestion that 'platonized' composition may be obtained		Promising propellants for motors up to very large sizes	

(a) Since this type of propellant has a large pressure index and high temperature coefficient motor tubes have to be made strong enough to withstand the highest pressures at the upper temperature limit and hence they are unnecessarily heavy and inefficient at lower temperatures.

(b) This applies to SU/K and similar propellants; improved formulations have been developed, but up to the present none have been cleared for Service use.

(c) The longer cracking life of cast double base propellant is probably due to the use of improved formulations rather than any intrinsic property; further investigations are required.

(d) Cast double base propellant manufacture is based on 'rifle-powder' the production of which in this country is inadequate even for small arms.

(e) The precise range depends on the plasticity of the